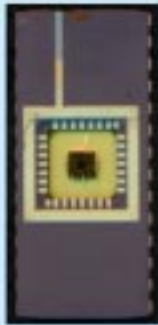
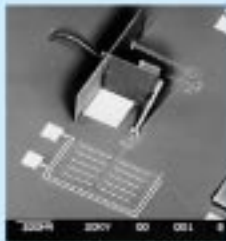


# Microelectromechanical Systems



**Dr. Albert P. Pisano  
MEMS Program Manager  
Electronics Technology Office  
Defense Advanced Research Projects  
Agency**

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<http://web-ext2.darpa.mil/ETO/MEMS>**

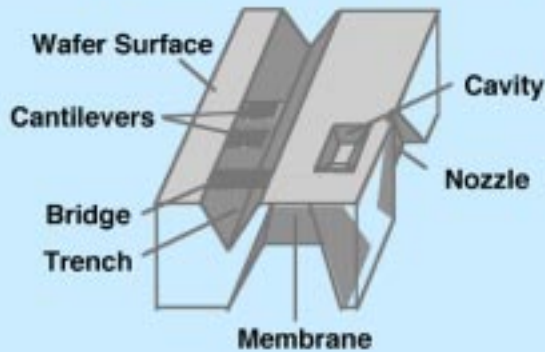


Good Morning, everyone. I am the new DARPA/ETO MEMS Program Manager, taking over for Ken Gabriel in his specific capacity as MEMS Program Manager of MEMS. Ken is now a Professor at Carnegie Mellon University, and today I'm happy to be briefing you on the DARPA/ETO MEMS Program. MEMS are truly a breakthrough technology.

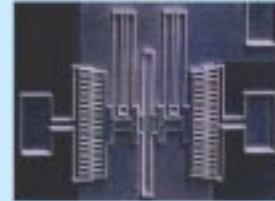
# **MEMS Description/Fabrication**



## **Common MEMS Fabrication Processes**



## **Surface Micromachining**



**MEMS co-locate sensing, computing, and actuating to change the way we perceive and control the physical world**

2

The acronym, MEMS, stands for “Micro Electro Mechanical Systems.” MEMS are composed of electronics and mechanical structures on the microscale. As such, they can include fluidic systems, optical systems, electromagnetic systems, electrostatic systems, in fact, almost any actuation and/or transduction technology that may occur on the macroscale.

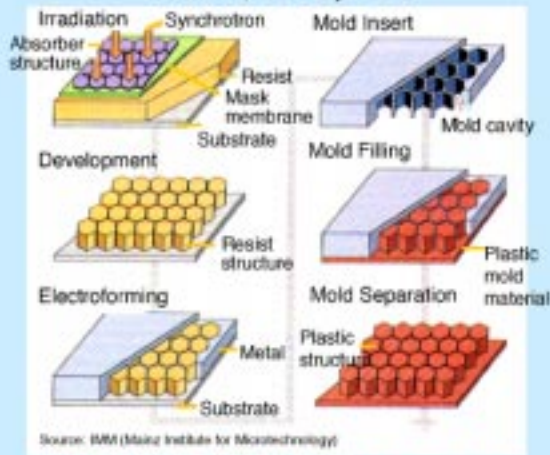
Since the electronics and mechanics are both incorporated on the microscale, MEMS make possible the co-location, on the microscale, of sensing, computing, and actuating. That is, at each and every discrete point on the microscale, one may have, simultaneously, sensing, computing, and actuating all going on. In this sense, MEMS are unique in that they can control flux at high spatial resolution and at high frequency response. And these fluxes include electron flux (current), as well as photon flux, heat flux, fluid flux, electromagnetic flux. And it all can be accomplished at low cost.

To the left is a schematic of bulk micromachining. To the right is a schematic of surface micromachining.

# MEMS Description/Fabrication

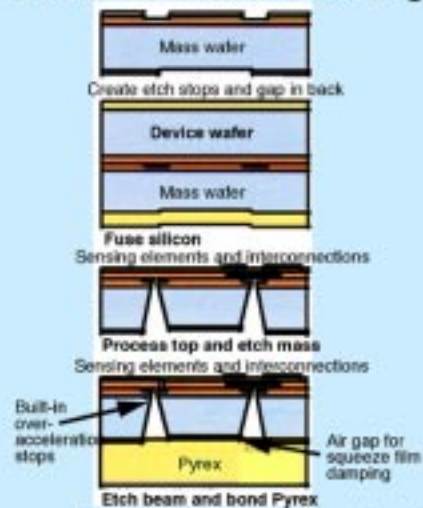


## LIGA\*, Deep UV



\*Lithographie, Galvanoformung, Abformung

## Wafer-to-Wafer Bonding



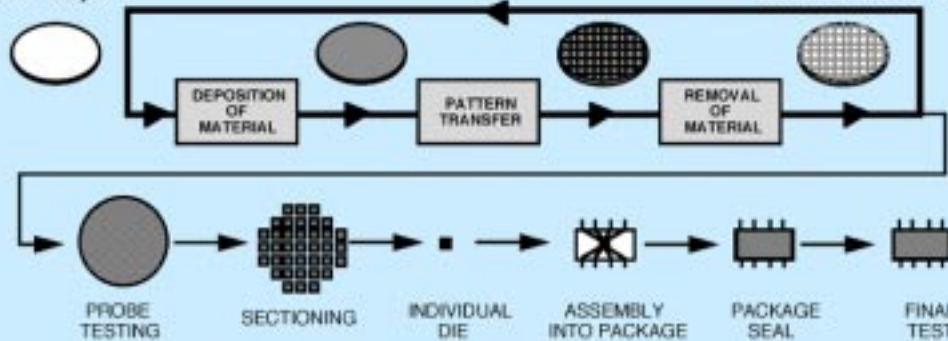
MEMS are a new way to make both mechanical and electrical components for microscale flux control

There are many other methods of micromachining. Almost as many as one can imagine. Here I show two other popular methods to fabricate MEMS. On the left, the LIGA process, invented in Germany. And on the right, wafer-to-wafer bonding, being pursued by several companies and Universities in the United States, as well as other laboratories around the world.

# MEMS Builds on Microelectronics Manufacturing



*Thicker films deeper etches fewer steps*      *Multiple Processing Cycles*      *Removal of underlying materials to release mechanical structures*



*Special probing, sectioning and handling procedures to protect released parts*

*Encapsulate some parts of device but expose others*

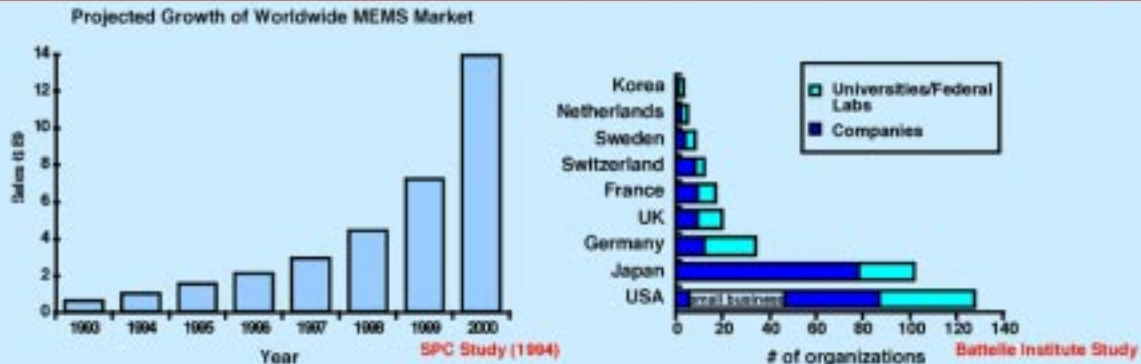
*Test more than just electrical functions*

4

Why is MEMS getting off to such a fast start? Well, one major advantage MEMS have is the large infrastructure in processing silicon wafers. This infrastructure was invented and funded by those working in microfabrication of electronic circuits. MEMS fabrication utilizes many of these methods, albeit with the process parameters changed in order to obtain functional mechanical structures as well as the requisite electronic structures.

This slide shows the current thinking on MEMS fabrication and packaging. As the next few years pass, I anticipate that this paradigm will change, and with greater frequency, MEMS will be fabricated directly onto the device into which they are to be integrated.

# MEMS Market and Industry Structure



- Not dominated by defense manufacturers

- Populated by diverse industries

- sensors
- industrial & residential controls
- electronic components
- computer peripherals
- automotive & aerospace electronics
- analytical instruments
- office equipment

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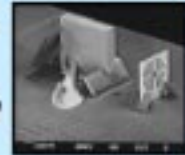
What does this emerging field of MEMS look like? One way to understand it is to take a look at who is making MEMS. Here is a snapshot of MEMS manufacturers all over the globe.



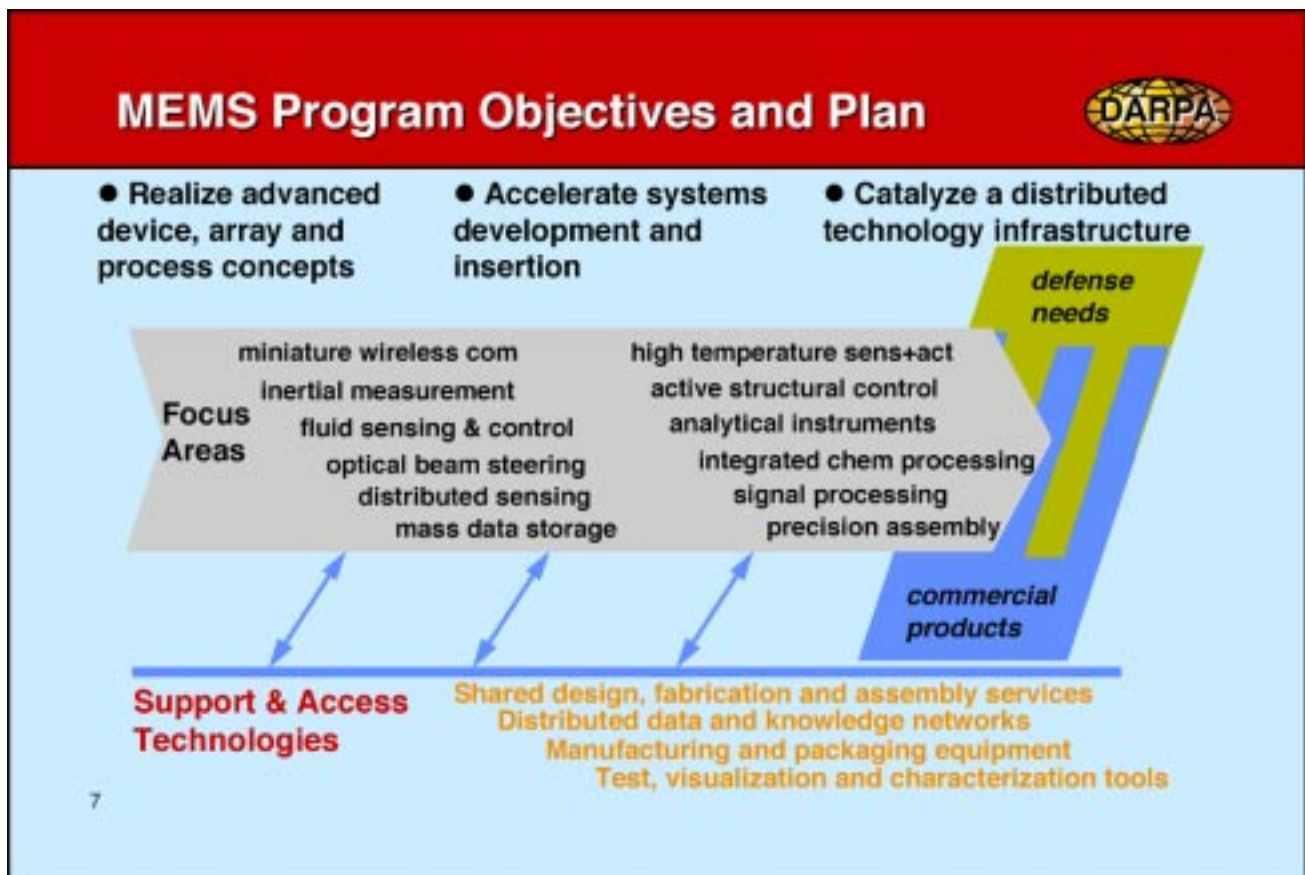
## Defense Applications of MEMS



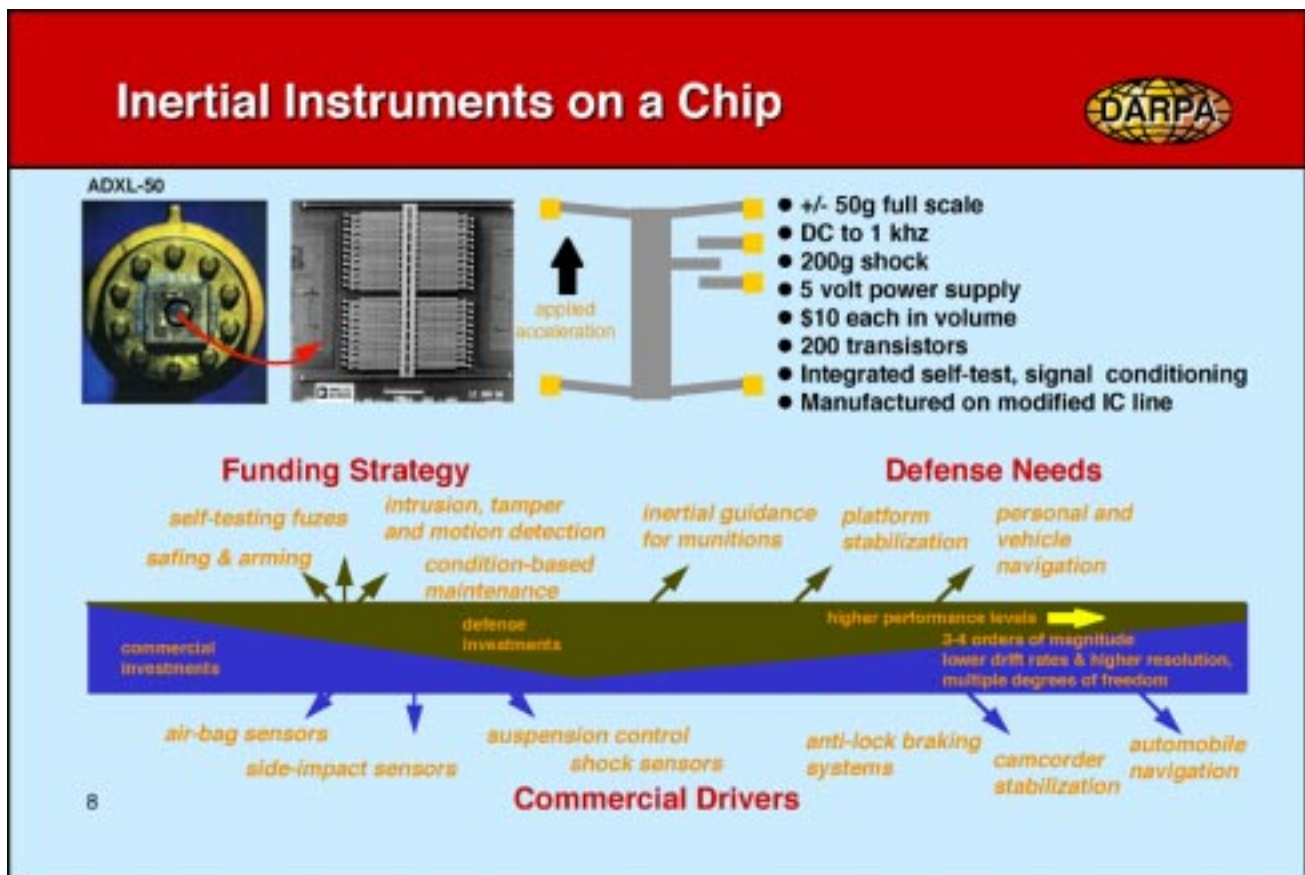
- **Inertial navigation units on a chip** for munitions guidance and personal navigation
- **Electromechanical signal processing** for ultra-small, ultra low-power wireless communication
- **Distributed unattended sensors** for asset tracking, environmental monitoring, security surveillance
- **Integrated fluidic systems** for miniature analytical instruments, propellant and combustion control
- **Weapons safing, arming and fuzing**
- **Embedded sensors and actuators** for condition-based maintenance
- **Mass data storage devices** for high density, low power
- **Integrated micro-optomechanical components** for identify-friend-or-foe systems, displays and fiber-optic switches
- **Active, conformable surfaces** for distributed aerodynamic control of aircraft and adaptive optics



The bottom line for the DARPA are Department of Defense applications of MEMS. Here are nine examples of MEMS applications to DoD needs.



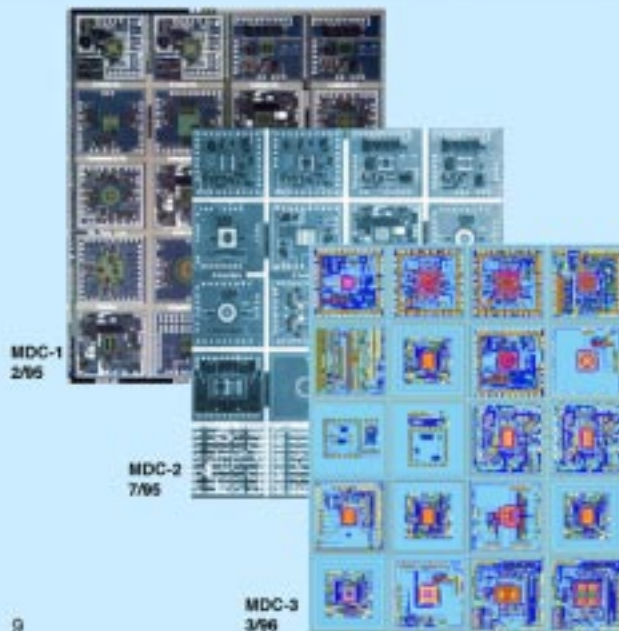
The basic objectives and plan for the DARPA/ETO MEMS Program are threefold: 1) realize devices, arrays, and processes, 2) accelerate the development of systems, and 3) make sure there is a distributed fabrication technology infrastructure in place nationally so that MEMS are available in the quantities needed to make a commercial impact. There are several focus areas to which MEMS are being applied, and these focus areas span both defense needs and commercial products. But common to all are the support and access technologies that make MEMS possible for both the DoD and the commercial sector.



On the upper left I show an example of a device that has achieved both commercial success and growing DoD relevance. This is the Analog Devices, Inc., micro accelerometer, the ADXL50. How might this one device affect both the Defense and the Commercial sectors? Let's look at the variety of applications (Defense above the green bar, Commercial below the blue bar). Note also that the leveraging of investment by DoD (DARPA in particular) is anticipated to ramp up to a point, and then decrease as the commercial sector begins to make major investments of its own. DARPA money is intended to spur the development of new MEMS, but not to permanently subsidize their manufacture.



## Multiple Device Chips



- z-axis accelerometers
- lateral accelerometers
- angular accelerometers
- integrator structures
- vibrational rate gyros
- high-Q EM filters
- lateral oscillators
- flow sensors
- resonant accelerometers
- EPROMs
- ADXL05
- ADXL50
- ADXL75
- signal processing elements

Analog Devices/UC Berkeley

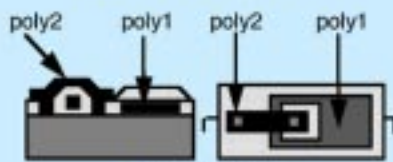
For the next part of my briefing, I review a series of interesting projects funded by the DARPA/ETO MEMS Program. Many of these were put into place by my astute predecessor. I'm carrying these forward, as well as initiating more projects during my tenure as MEMS Program Manager.

Here I show the "multi project chip" fabricated by the team of Analog Devices, Inc., and the University of California at Berkeley. Note that in one technology and on one wafer one may make devices falling into these 14 categories. And we are not limited to just these 14. The applications of the devices fabricated on this one chip are many.

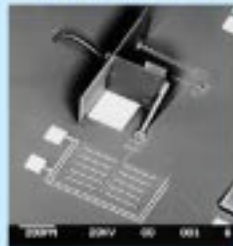
# Optical MEMS Components



Fabrication sequence



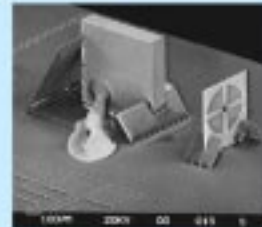
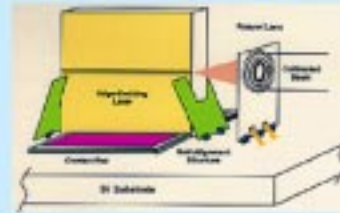
Corner cubes



- Out-of-plane hinged structures fabricated in-plane
- Integrated micro-optomechanical components that are subsequently "assembled"

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Integrated optical components



- Corner cube reflectors (low-power, line-of-sight communications and identify-friend-or-foe)
- Optical interconnects and aligners

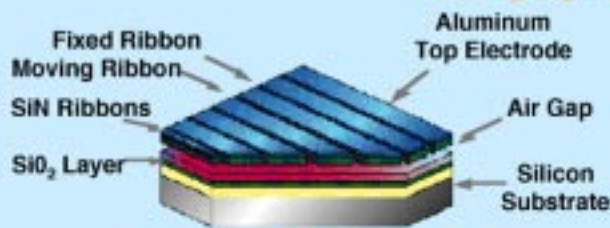
UCLA

Here is work with roots at UC Berkeley, and major development at UCLA, as well as continuing progress at UC Berkeley. The innovative concept here is the “fold-up” assembly of planar structures into three-dimensional structures. Since microfabrication depends on the photolithographic process, the advantage here is that well-known planar fabrication processes may be used to build the “unfolded” version of three-dimensional structures, and then a process as simple as a water-rinse may be used to push and lock the structures into their three-dimensional position.

# Optomechanical Displays



## Grating Light Valves

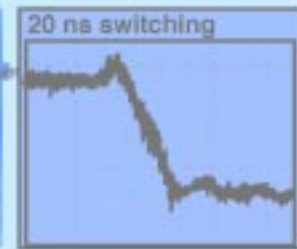
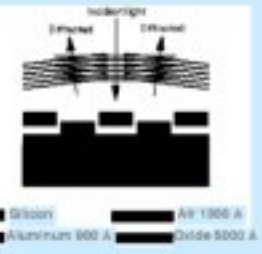


- Silicon surface-micromachined, deformable grating modulator
- No phosphors or liquid crystals
- Low-power, bi-stable switching
- RGB color capability
- 20 nanosecond switching time
- Full motion video
- Digital gray scale

### Dark State



### Bright State



**Silicon Light Machines**

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There is more than one way to apply MEMS to optics. The DMD depends on having multiple sources of light, each with a different color, to form a color image. Here is a way to form any color of light from a plain white illumination. The moving ribbons being pursued by Silicon Light Machines actually use interference to construct the correct wavelength of light to form images. This grating moves in response to electrical signals, making possible an array of “pixels” that may assume any color at any time.

# Environmental Monitoring Sensor Cluster



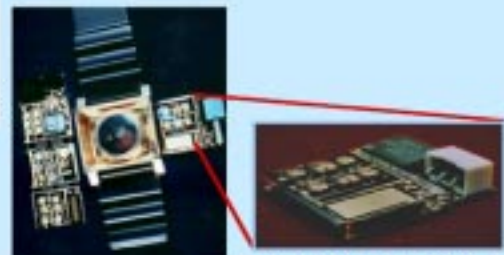
Wristwatch-sized generic sensor cluster - measurement of temperature, barometric pressure, & vibration



Telemetry Range: 50 ft.  
 Average Power Dissipation: <500  $\mu$ W  
 Portable Operating Life: 120 days  
 Barometric Pressure Range (Abs): 550-850 Torr  
 Ambient Temperature Range: -30 to +60° C  
 Humidity Measurement Range: 30-90% RH  
 Acceleration Range:  $\pm$  2g

## Specific Applications:

- Air Force Phillips Laboratory: Airport Weather Monitoring
- Naval Research Laboratory: Unmanned Air Vehicle Applications
- Naval Research Laboratory: Ocean Buoy-Mounted Environmental Sensing
- Marine Science Advisor: Environment/Weather Sensors
- Department of Transportation: Airport Weather Monitoring



University of Michigan

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MEMS may be used to revolutionize sensing over long distances and in remote locations. Here is a miniature sensor cluster being developed by researchers at the University of Michigan. This cluster is being investigated by over five government organizations.



# Low Power Wireless Integrated Microsensors (LWIM)



- Distributed, autonomous, wireless microsensor network with signal processing decision capability
- Single-chip RF transceiver integrated with sensors and integrated RF components
- Low power/low noise analog signal processing based on weak inversion CMOS



LWIM-I node



LWIM-I low power receiver and base station interface



PC-notebook base station and LWIM Windows interface

## **Emerging Applications**

battlefield awareness  
situational awareness  
munitions targeting  
condition-based maintenance  
environmental monitoring  
biomedical monitoring  
civil safety and security  
commercial manufacturing  
transportation

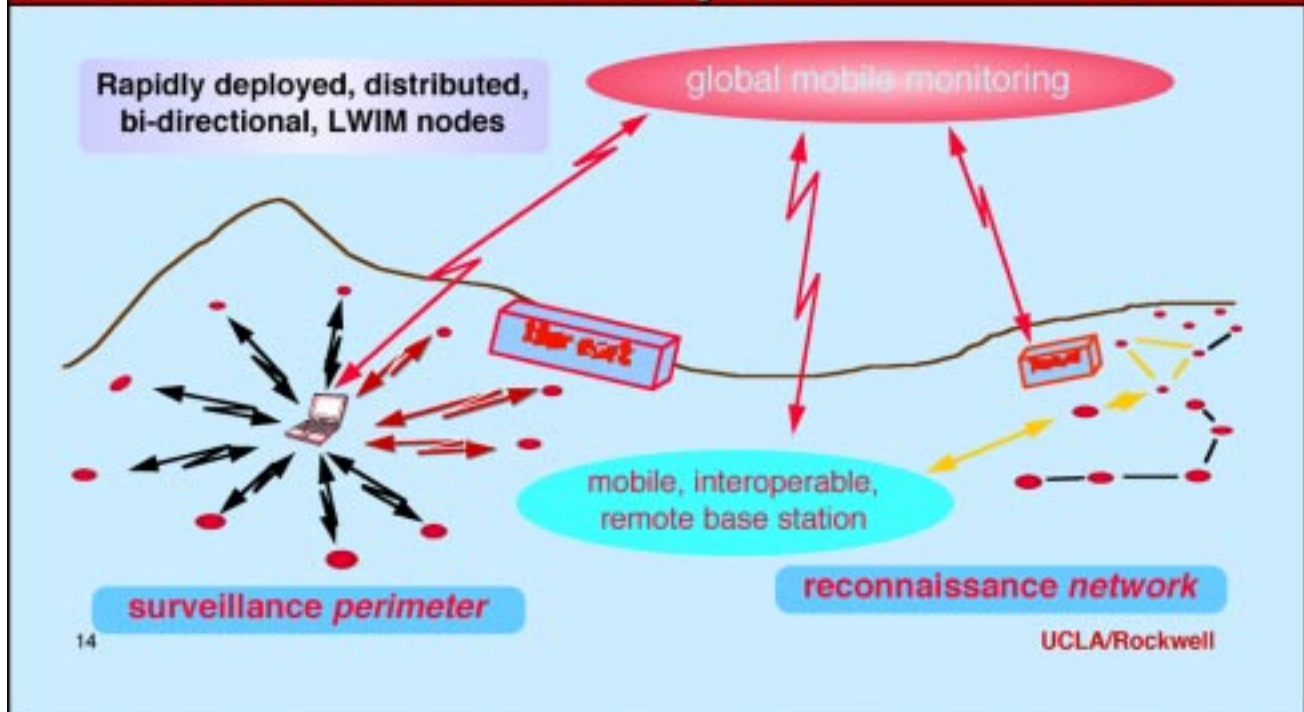
surveillance, perimeter and base security  
detection, identification, tracking  
munitions impact, target location  
vehicle, powerplant, transmission, propulsion  
external and internal local and global control  
personnel health status monitor  
residence, commercial, public structures, urban  
precision machining with low cost tools  
IVHS, vehicle control

**UCLA/Rockwell**

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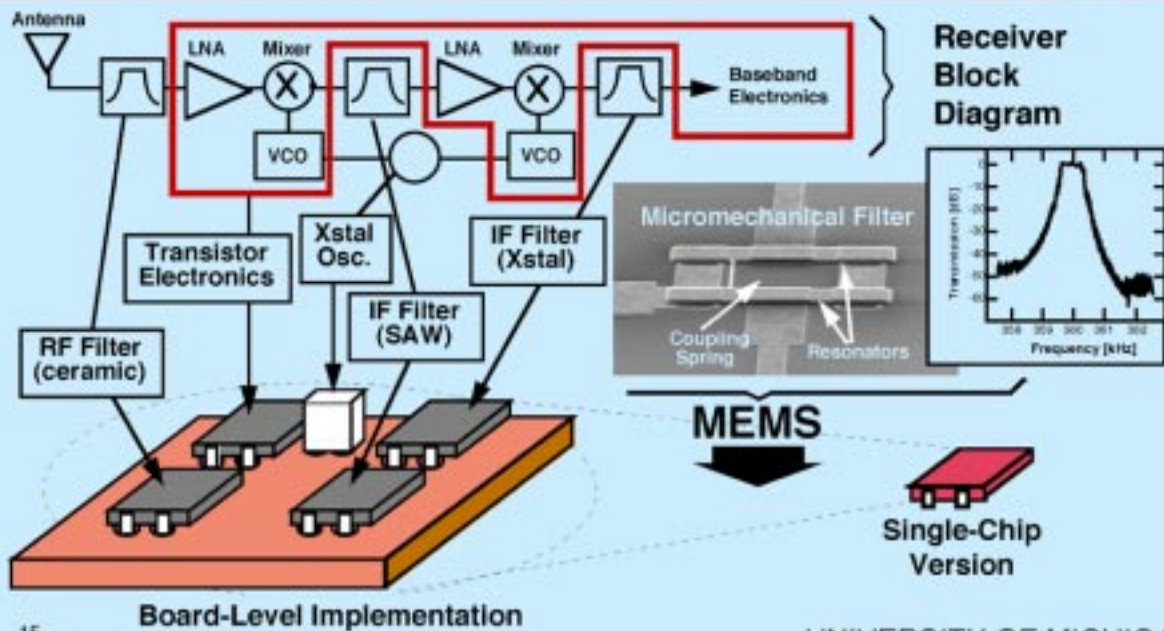
The LWIM project, jointly operated by UCLA and Rockwell, is pioneering a low power, wireless microsensor network with extreme application to battlefield awareness.

## LWIM Intelligent Distributed Nodes: Tactical Remote Sensor Systems



Here are the two ways LWIM system may operate. A distribution of nodes (randomly dropped from an aircraft, for example) need not be placed in any precise locations. When on the ground, they self-organize into a network that can either establish a perimeter for surveillance, or, by passing information among themselves, work as an effective reconnaissance network. Communications with either ground or air units is made possible by LWIM units that either work together, or by one particular LWIM unit of higher radio broadcast power.

# Radio-Frequency MEMS



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UNIVERSITY OF MICHIGAN

I believe that MEMS will play a role in the miniaturization of transceivers. On the lower left is shown a board-level implementation of a radio. Most of the components there are not integrated into the transistor electronics chip. MEMS will make possible that integration so we may achieve, truly, a radio on a single chip. This slide depicts work ongoing at the University of Michigan.

# Radio Frequency MEMS



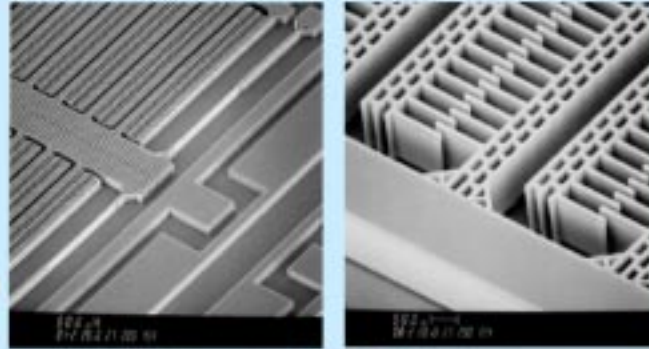
- **Technical challenges**

- Antenna, Frequency Band, Size, Weight, Power

- **MEMS solution**

- Replace discrete, off-chip components (switch, varactor, inductor)
  - Replace entire electrical circuits with electromechanical signal processing (filters, oscillators, modulators, de-modulators)

- **Single Crystal Silicon**
- **Superior Mechanical Properties**
- **High Aspect Ratio (20 to 1)**
- **Higher Linearity**
- **Large Tuning Ratio (> 6.5 to 1)**



SEM micrographs of the MEMS tunable capacitor

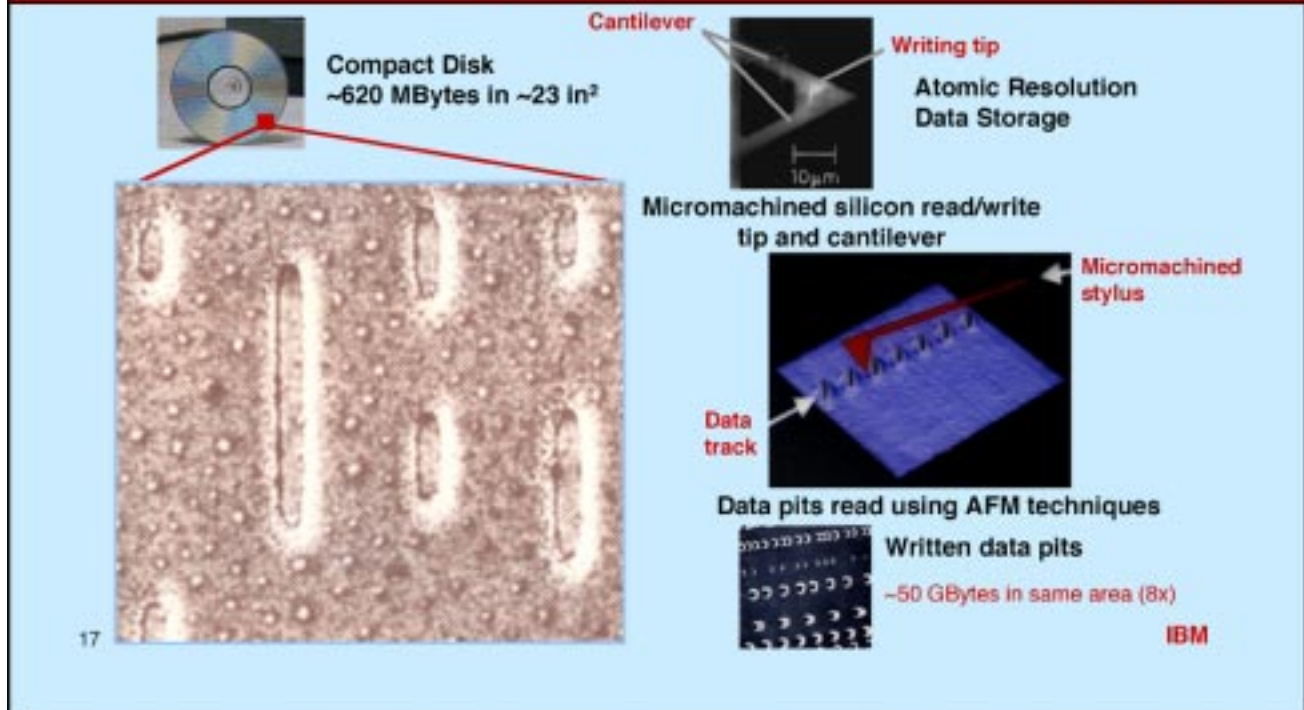
Rockwell

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We see here just one way in which MEMS can bring about the miniaturization of radios, being pursued at Rockwell for the miniaturization of Antenna Interface Units. Below, I show a MEMS varactor, basically just a capacitor whose value I can change with a voltage command. With this varactor, I can drastically reduce the size, weight, and power of radios, all the while increasing performance, since the MEMS varactor has lower insertion losses than macro devices do. Along with varactors have been constructed MEMS switches and MEMS signal processing networks. These technologies all work better than their electronic counterparts. As a Mechanical Engineer, I'm thrilled by all of this since it means that electromechanical signal processing may be supplanting purely electrical signal processing and this represents the Mechanical Engineering revenge upon the transistor!



# Mass Data Storage



On the other side of the country, IBM in San Jose is pursuing a method of reading mechanical pits arranged into data tracks.

A compact disk is known for its incredible data density. This is approximately 620 Megabytes in just 23 square inches. But using this method of mechanically reading pits in a carbon film, one may achieve a storage of over 50 Gigabytes in the same area! An increase of almost 100x. What's happening here is that an incredibly small writing tip is scanning the surface, staying just a small fraction of an atom away, since it actually measures the repulsive force from individual atoms. As the tip is actuated up and down to avoid contact with the surface, a control system decides if a bump is encountered, and the data is encoded in the pattern.

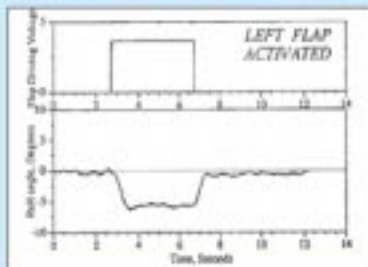
# Active Conformable Surfaces



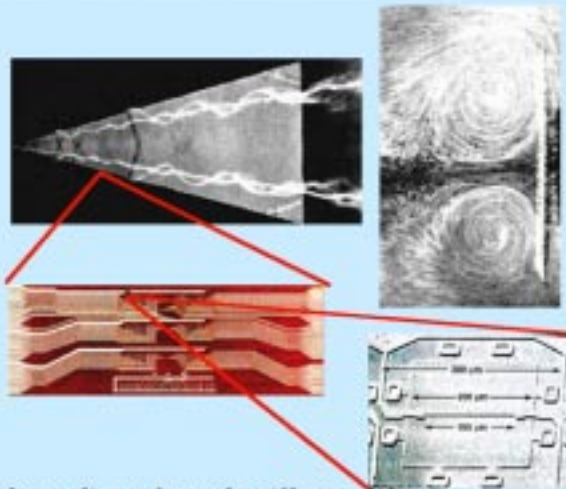
## Advanced Aerodynamic Control



**Distributed MEMS sensors & actuators control separation of leading-edge vortices**



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- Aircraft and projectiles with no large, discrete control systems
- Higher maneuverability, greater lift, reduced drag

UCLA/CalTech

Let's switch from the micro to the macro. One of the hallmarks of a great MEMS system is its ability to control flux on the microscale in order to obtain effects on the macroscale. This project (joint between UCLA and Cal Tech) showed just how to do that for aircraft. The separation of the leading edge vortex on a swept airfoil can be used to strongly adjust the lift and drag on that airfoil. Control that, and you control the airplane. But the flow separation can be "tripped" by just the tiniest of bumps ... if you know exactly where to put the bump. Now, make the bump bigger and smaller and you can trip or not trip the flow separation. And viola ... microactuators moving around airplanes! Now, this hasn't been done for full-sized aircraft yet, but recent work on 1/6 size scale models shows that MEMS actuators can actually be used to maneuver for climb, descent, rolls, and turns.

## MCNC-DARPA Multiproject Chip Run



MUMF#13

MCNC-DARPA MEMS Multiproject Run

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MCNC

Wide access to MEMS Fabrication is a major goal of the DARPA/ETO MEMS Program. Here is a multi-project chip fabricated at MCNC, the Micromachining Center of North Carolina. Of special note is the fact that chips for over 40 users are all fabricated on this one wafer, minimizing the cost to each user.

## Multi-User MEMS Projects (MUMPs)



**Accelerating innovation and commercialization by providing MEMS fabrication technologies to multiple, remote users**

\$1400 + design → MCNC (10 weeks later) → fifteen 1 cm x 1 cm MEMS chips with your design



**30% of users are getting their first access to MEMS technology through MUMPs**

~ 550 projects, 500 users in total, 90 organizations

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MCNC

All you need is approximately \$1400 and a PC. After downloading the software to do your layouts, you can virtually upload your artwork to MCNC and, in 10 weeks, get a dozen chips with your own design on it! This has been going on since May 1994, and the frequency of runs has increased from a few per year to six per year. Note the graph ... Federal and Industry Labs are using MCNC to a great extent, dramatically showing the involvement of these groups in the MEMS field. Over 50 users have used MUMPS to date, for a total of 550 different projects. I figure that 30% of all users are getting their first access to MEMS by going through MUMPS at MCNC.